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FIELD-ALIGNED ELECTRIC CURRENTS
AND THEIR MEASUREMENT BY
THE INCOHERENT BACKSCATTER TECHNIQUE

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ABSTRACT

Field-aligned electric currents flow in the magnetosphere in many situations of fundamental geophysical interest. It is shown here that the incoherent back-scatter technique can be used to measure these currents when the plasma line can be observed. To our knowledge this has not been proposed before. The technique provides a ground-based means of measuring these currents which complements the rocket and satellite ones.

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INTRODUCTION

Field-aligned currents in the magnetosphere exist in various geophysical contexts of fundamental interest. In the setting of auroral physics they were originally postulated by Birkeland and are now widely known by his name.

From the experimental viewpoint most is known about these current in the auroral setting from the work of Zmuda et al (1966, 1967, 1970) Choy et al (1971), Cloutier et al (1973, Fairfield (1973), Thiele and Praetorius (1973, Vondrak et al (1971), Kawasaki et al (1974) Zmuda and Armstrong (1974), Ledley and Farthing (1974) and others. From the theoretical point of view these auroral currents have appeared in the works of Alfvén (1939, 1940), Piddington (1959), Cole (1961, 1963, 1971, 1974), Fejer (1963), Kern (1962), Bostrom (1964), Cummings and Dessler (1967), Swift (1963, 1965), Shield et al (1969), and others (see Anderson and Vondrak 1975, for a review). In the context of the quiet variations of the geomagnetic field they have appeared, e.g., in the work of Dougherty (1963), Van Sabben (1962), Mishin et al. (1968), Lemaire and Scherer (1974), Cocks and Price (1969), and Stening (1969). The inference of field-aligned current strengths using magnetometers on board satellites is made difficult by choice of baselines in the records and also by the complications of temporal as well as the spatial variations of the magnetic field.

As will be demonstrated the incoherent backscatter technique is capable of giving absolute measures of the field-aligned current from the strongest known,

to ones which are two orders of magnitude less. This constitutes a great improvement in our potential for knowledge of these currents.

The field aligned current density j is given by

$$j_{\parallel} = j_{i\parallel} + j_{e\parallel} = n_e e (\underline{v}_i - \underline{v}_e)_{\parallel} \quad (1)$$

where

$\underline{v}_{i,e}$ = velocity of ions, electrons

e = electronic charge

n_e = electron density

\parallel denotes the component along the magnetic field (\underline{B})

Consider an incoherent backscatter device receiving signals from the direction of the magnetic field. It is well known (see Bauer 1975 for a review) that n_e can be found from the intensity of the signals received; $\underline{v}_{i\parallel}$ can be found from the shift of the so called "ion spectrum"; and we show here that $\underline{v}_{e\parallel}$ can be found from the shift of the "plasma line" provided it is excited, e.g., by photoelectrons or auroral electrons at the same time. It follows that the current j_{\parallel} can be measured absolutely and directly with this ground-based technique.

THEORY

Measurement of $\underline{v}_{e\parallel}$

Since the theory of measurement of n_e and $\underline{v}_{i\parallel}$ is well documented we give here the theory for the measurement of $\underline{v}_{e\parallel}$. Since we shall be concerned only with velocities \parallel to \underline{B} we shall hence forth drop the subscript \parallel . It is supposed

that photoelectrons or auroral electrons traveling along the geomagnetic field excite longitudinal waves in the ionospheric plasma.

Consider then the dispersion relation for longitudinal waves of angular frequency (ω) in a plasma without magnetic field, or for a wave vector \underline{k} parallel to the magnetic field. It can be written (Stix 1962)

$$1 = \omega_{pe}^2 \int_{-\infty}^{\infty} \frac{f_e(v) dv}{(\omega - kv)^2} + \omega_{pi}^2 \int_{-\infty}^{\infty} \frac{f_i(v) dv}{(\omega - kv)^2} \quad (2)$$

where $f_e(v)$ is the one dimensional electron velocity distribution, $f_i(v)$ the one dimensional ion velocity distribution, ω_{pe} the electron plasma angular frequency, ω_{pi} the ion plasma angular frequency. Note that $f_e(v)$ relates to both the thermal and the suprathermal electrons.

In the present problem we are only interested in the real part of the solutions in the vicinity of $\pm \omega_{pe}$. In this case equation (2) can be approximated by a power series expansion:

$$1 = \frac{\omega_{pe}^2}{\omega^2} \left(1 + \frac{2k}{\omega} \langle v_e \rangle + \frac{3k^2}{\omega^2} \langle v_e^2 \rangle \right) + \frac{\omega_{pi}^2}{\omega^2} \left(1 + \frac{2k}{\omega} \langle v_i \rangle + \frac{3k^2}{\omega^2} \langle v_i^2 \rangle \right) \quad (3)$$

In order to simplify this expression it is necessary to make order of magnitude computations for ω in the vicinity of $\pm \omega_{pe}$. The dominant term of the ionic component is, for oxygen ions, approximately equal to 3×10^{-5} times the major electronic term. The term dependent upon the mean square of the electron velocity is of the order of 1/10 of the electron dominant term for mean

ionospheric conditions (T_e 1000K, f_p 5×10^6 Hz) and a wavelength of 0.3 m corresponding to a working frequency of 10^9 Hz. The term dependent upon the mean electron velocity reaches 1/100 of the dominant term for the same ionospheric conditions and a mean velocity of 5000 m/s.

Therefore the ionic component can be neglected with respect to all the electronic components and the dispersion relation for the solutions in the vicinity of $\pm \omega_{pe}$ can be written as:

$$1 = \frac{\omega_{pe}^2}{(\omega - k \langle v_e \rangle)^2} \left[1 + \frac{3k^2}{(\omega - k \langle v_e \rangle)^2} (\langle v_e \rangle - \langle v_e \rangle)^2 \right] \quad (4)$$

In the vicinity of $\pm \omega_{pe}$ this expression has two solutions:

$$\omega_r - k \langle v_e \rangle = \pm \omega_0$$

or

$$\omega_r = k \langle v_e \rangle \pm \omega_0 \quad (5)$$

In other words the two solutions are now located symmetrically with respect to $k \langle v_e \rangle$ rather than with respect to zero. These solutions are approximately given by

$$(\omega_r - k \langle v_e \rangle)^2 = \omega_{pe}^2 + (3KT_e) k^2 \quad (6)$$

where T_e is the apparent temperature of the electron gas (including the photoelectrons), and K is Boltzmann's constant.

Whatever is the second term of the right hand side of (6) the important point is that a drift of the whole electron gas induces a doppler shift in the location of

the two solutions of the dispersion relation close to $\pm\omega_{pe}$. In terms of an incoherent scatter experiment a drift of the electron gas introduces a summed shift in the locations of the two plasma lines (1, 2) with respect to the central (i.e. transmitted) frequency (ω_c)

$$\Delta(|\omega_r - \omega_c|)_{1+2} = 2k \langle v_e \rangle$$

e.g. for an electron drift of 1000 m/s, and a wavelength of .30 m

$$\Delta(|\omega_r - \omega_c|)_{1+2} = 2 \times \frac{2\pi}{0.3} \times 2 \times 10^3 \text{ rad s}^{-1}$$

$$\approx 1.3 \times 10^4 \times 2\pi \text{ rad s}^{-1}$$

which can be measured. It follows that

$$\frac{\Delta\omega}{\omega_c} = \frac{\Delta(|\omega_r - \omega_c|)_{1+2}}{\omega_c} = \frac{4V_e}{c} = \frac{4J_{e\parallel}}{n_e e c}$$

The measurement of $\Delta\omega/\omega_c$ is then convertible to a measure of v_e .

Errors

As for the ion spectrum the main cause of error is of statistical origin. However, contrary to the case of the ion spectrum the spectral shape of the plasma line is not determined by the ionospheric parameters alone but also by the distribution of the electron concentration in the volume being observed, i.e. by the geometry of the experiment. We make the reasonable assumption, in view of current experiments, that the plasma lines can be sketched as shown on Figure 1. The flanks of the lines are characterized by approximately linear slope from the maximum signal S_{\max} to the noise level over frequency intervals Δf .

We assume further that filters of width Δf are being used. This leads to the following estimate of the error in the electron velocity for a noise level N larger than the signal (Petit 1968, Evans 1969)

$$\Delta v_e \approx \pm \frac{N}{S_{\max}} \frac{\sqrt{\Delta f}}{\sqrt{t}} \frac{\lambda}{\sqrt{2}} \text{ m/s}$$

where t is the time of integration λ the wavelength. Table I gives the errors in velocity v_e or electron current density (for an assumed electron density of $5 \times 10^{11} \text{ m}^{-3}$), for Δf varying between 25 and 100 kHz, a signal to noise ratio varying between 1/100 and 1, an integration time of 1000 sec and $\lambda = 0.3 \text{ m}$. It will be shown that the accuracies mentioned in Table I are suitable for most cases for the measurements of field-aligned currents during quiet or disturbed conditions.

In Figure 2 are shown values of $\Delta\omega/\omega_c$ as functions of $j_{e\parallel}$ and n_e . With presently available equipment, values of $\Delta\omega/\omega_c$ of order 10^{-6} are easily obtainable. On this figure are indicated ranges of current densities appropriate to disturbed and quiet conditions. Also indicated on Figure 2 are values of v_e for various values of $j_{e\parallel}$ and n_e . As seen on Table I signal to noise ratio of 0.01 should allow measurements of currents ($j_{e\parallel}$) for disturbed conditions, and signal to noise ratio of 0.1 should allow measurements of $j_{e\parallel}$ in both quiet and disturbed conditions.

The ion drift velocity v_i is obtained from the shift of the "ion spectrum." The two measurements combined according to equation 1 will produce the field-aligned current j_{\parallel} .

Several special cases suggest themselves (a) $j_{\parallel} = 0$, combined with bulk flow of plasma along \underline{B} . In this case both the "ion spectrum" and the "plasma lines" are doppler shifted by equal amounts.

(b) $j_{e\parallel} \neq 0$ but $j_{i\parallel} = 0$. In this case the "ion spectrum" will be unshifted but unsymmetrical on account of the electron motion, and the plasma lines will be doppler shifted.

(c) In the general case $j_{e\parallel} \neq 0$ and $j_{i\parallel} \neq 0$. The ion-spectrum will be shifted and unsymmetrical and the plasma lines doppler shifted. The asymmetry of the ion spectrum can be related to $(v_i - v_e)$. However, the asymmetry of the ion spectrum would relate only to the relative drift of the thermal electrons with respect to the ions and might indicate, if ever measurable, a relative drift of the photoelectrons or auroral electrons with respect to the thermal electrons by comparison with the shift of the plasma lines. This will be particularly important in deciding the contribution of energetic and thermal electrons to Birkeland currents in the auroral zone. In situations where the photoelectron contribution to the current is negligible compared to that of thermal electrons, this will provide a redundant check on the electron velocity measured by the shift in plasma lines.

GEOPHYSICAL SITUATIONS OF INTEREST

Electric currents flowing along the geomagnetic field occur in many geophysical situations of interest. However, it is difficult to measure them in situ. Of the ground based techniques, incoherent scatter offers the opportunity to study

these currents in considerable detail both in time, and altitude distribution. We present a discussion of the various situations in which the currents occur.

In auroras

Birkeland considered field-aligned currents in relation to the auroral electrojet. Theories have been proposed for them in this context. Measurements from satellite borne magnetometers have been interpreted by Zmuda and Armstrong (1974) in terms of field aligned currents of strengths up to about 5×10^{-5} A/m². Such a current requires a charge flux of 3×10^{14} particles/m² S. With ionospheric densities of about 5×10^{11} /m³, this implies (in the case where all the current is carried by electrons) an average electron velocity of 6×10^2 m/s, even though the current may be supplied largely by fewer faster moving particles. Zmuda and Armstrong (1974) have reviewed the observations of energetic particles which may contribute to the current. Earlier Cole (1963) showed that field aligned currents might be studied from the ground using accurate parallactic imaging of auroral rays. Such currents cause a twist in the geomagnetic field and a consequent change in the direction of the geomagnetic field in space. It is suggested that the parallactic method, calibrated by the backscatter technique of measuring current, may form a useful and less expensive additional system for ground-based study of the currents on a wider geographical scale.

The Cusp

In the vicinity of the polar cusp ionosphere, field-aligned current is highly structured and a current of about 10^{-4} A/m² (10^{-9} emu) has been interpreted there during a large fluctuation observed by a rocket borne magnetometer (Ledley and Farthing 1974). Though the current is probably carried by energetic electrons from the solar wind the current does imply a mean electron velocity (assuming a density of order 5×10^{11} m⁻³ at the rocket altitude) of about 1.2×10^3 m/s along the geomagnetic field

Asymmetric Dynamo Action

On account of asymmetries of magnetic field, wind fields or ionospheric electrical conductivity current will flow parallel to the geomagnetic field to maintain continuity (Dougherty 1963, Van Sabben 1966, Mishin et al. (1968), Maeda and Murata 1965, 1968, Cocks and Price 1969, Stenning 1969, Cole 1971). Currents of strengths in the range 5×10^{-6} A/m² (5×10^{-11} emu) to 5×10^{-5} A/m² (5×10^{-10} emu) have been estimated in these studies. Combined with electron densities of order 10^{10} m⁻³ (at 1000 altitude) or about 5×10^{11} m⁻³ in the F region this implies electron velocities in the range 6×10^1 m/sec to 3×10^4 m/sec.

These currents should be expected to flow virtually at all times during the day on account of the permanent asymmetry of conjugate ionospheric conductivities and dynamo fields.

Magnetosphere Currents

By continuity, the field aligned current at the top of the ionosphere (say in the F region) can be related to that in the magnetosphere by

$$j_A = j_I$$

where A = cross section of tube of force with unit cross section at the ionosphere (A) = B_I/B . Where B denotes magnetic induction and subscript I denotes the ionosphere. It follows that along a magnetospheric field line

$$\frac{ne}{B} B_I = j_I = \text{constant}$$

or

$$v = \frac{j_I B}{ne B_I}$$

It follows that only in a magnetotube with $n \propto B$ would v be constant. If n falls more rapidly with altitude than this, then some advantage in terms of $\Delta\omega/\omega_c$ (see equation 7) is gained by studying the currents at higher altitudes. In any case such a study should be done in order to try to locate the source region of these currents.

The Pre-Dawn Ionosphere

Sometimes the ionosphere is sunlit at the conjugate place before sunrise on the local ionosphere. This causes heating of the local ionosphere by the energy of photoelectrons absorbed in the geomagnetic field tube of plasma. The accompanying predawn enhancement in airglow may be due to thermal excitation by F region electrons (Cole 1965) direct excitation (Carlson 1966) or recombination

due to electrodynamically induced lowering or downward diffusion of the F region (Carlson and Walker 1972) or a combination of these. In the case of lowering of the F region by an electric field, field aligned electric current may perhaps be involved. Indeed one would expect field aligned current to exist at these times on account of the asymmetry of the ionospheric conductivity and dynamo fields in the conjugate ionospheres. The measurement of electric current at these times should shed further light on these interrelated geophysical phenomena.

Eclipses

Eclipses of the sun either locally or at the conjugate point provide opportunities to study the field aligned currents associated with the electrodynamic asymmetry induced in the ionosphere.

Within the Ionosphere

Within the ionosphere winds of different direction at different altitude have different dynamo effects and compensating electric currents parallel to \mathbf{B} should flow in order to maintain $\text{div } \mathbf{j} = 0$. The study of the scale sizes and magnitudes of these currents from the ground will add immensely to our knowledge of ionospheric electrodynamics.

Magnetic Substorms

The interchange of tubes of plasma in the geomagnetic field must be accompanied by field-aligned currents (Cole 1971). This occurs during magnetic substorms. It will be of interest to study such currents occurring equatorwards of

the auroral electrojet where they may be weak and not yet reached by the satellite magnetometer, because of problems of baseline determination.

Break-up of Intertropical red arc

At night the intertropical red arc frequently "breaks-up", causing airglow enhancements of irregular shapes and sizes (Barbier 1958, Petersen et al., 1966). These are likely caused indirectly by irregular electric fields which cause the interchange of tubes of plasma at low magnetic latitudes. These interchanges will be accompanied by field-aligned currents (Cole 1971). The arcs occur at about $\pm 15^\circ$ from the magnetic equator. The incoherent backscatter facility at Arecibo, Puerto Rico is well placed for the study of the field aligned currents that must accompany the break up of the intertropical red arc.

Artificial stimulation of the plasma line

By the artificial introduction of electron beams from a satellite, or space laboratory into the ionosphere the plasma line may perhaps be stimulated at night at mid-latitudes for subsequent observation by ground based incoherent backscatter facilities.

Space Shuttle or Orbiting Incoherent Scatter Systems

It would add greatly to our knowledge of field aligned currents to operate a mobile incoherent facility in space, making the measurements suggested in the foregoing.

CONCLUSION

It has been demonstrated that the incoherent backscatter technique may be used to study virtually the whole range of geophysical phenomena involving field-aligned electric currents. In that it is able to give absolute measures of currents stronger than about 10^{-7} A/m² (10^{-12} emu) it has the potential for the greatest dynamic range of the techniques presently available to study these currents.

The existing facilities at Arecibo (Puerto Rico), Saint Santin (France), Millstone Hill (USA) and Chatanika (USA) are well placed for many of the studies suggested in the foregoing report. The proposed EISCAT facility in Scandinavia as planned will be well placed to study the field-aligned currents associated with auroral current systems. Improvements in the signal to noise ratio on account of proximity to the currents would enable the use of lower power systems on a Space Shuttle or orbiting satellite.

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TABLE I
Statistical Errors Δv in m/s (or Δj in Am^{-2} for $n_e = 5 \times 10^{11} \text{ m}^{-3}$)
for given Δf (see fig. 1) and signal to noise ratios (S/N) and for
an operating wavelength $\lambda = .3\text{m}$ and an integration time $t = 1000 \text{ s}$.

S/N Δf	25 kHz	50 kHz	100 kHz
1/100	$\Delta v = 106 \text{ m/s}$ $\Delta j = .85 \times 10^{-5} \text{ Am}^{-2}$	150 m/s $1.2 \times 10^{-5} \text{ Am}^{-2}$	210 m/s $1.68 \times 10^{-5} \text{ Am}^{-2}$
1/10	$\Delta v = 10.6 \text{ m/s}$ $\Delta j = .85 \times 10^{-6} \text{ Am}^{-2}$	15 m/s $1.2 \times 10^{-6} \text{ Am}^{-2}$	21 m/s $1.68 \times 10^{-6} \text{ Am}^{-2}$
1	$\Delta v = 1.06 \text{ m/s}$ $\Delta j = .85 \times 10^{-7} \text{ Am}^{-2}$	1.5 m/s $1.2 \times 10^{-7} \text{ Am}^{-2}$	2.1 m/s $1.68 \times 10^{-7} \text{ Am}^{-2}$

FIGURE CAPTIONS

Figure 1. Schematic representation of the plasma lines.

Figure 2. Diagram showing the inter-relationships of $\Delta\omega/\omega_c$, n_c , j , v_c .

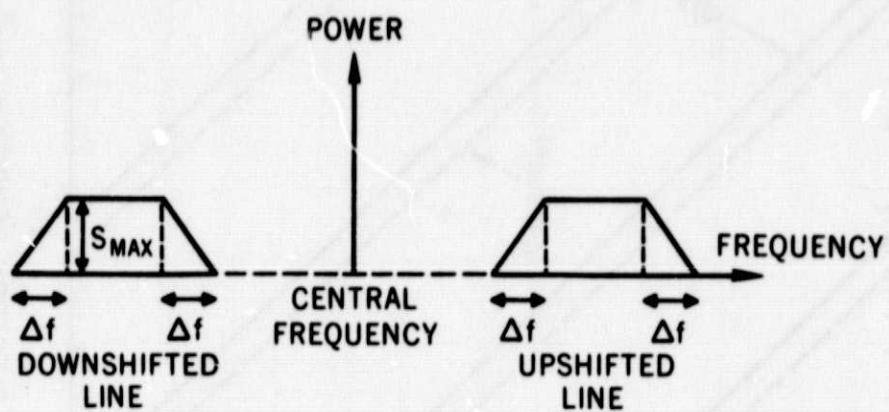


Figure 1. Schematic representation of the plasma lines

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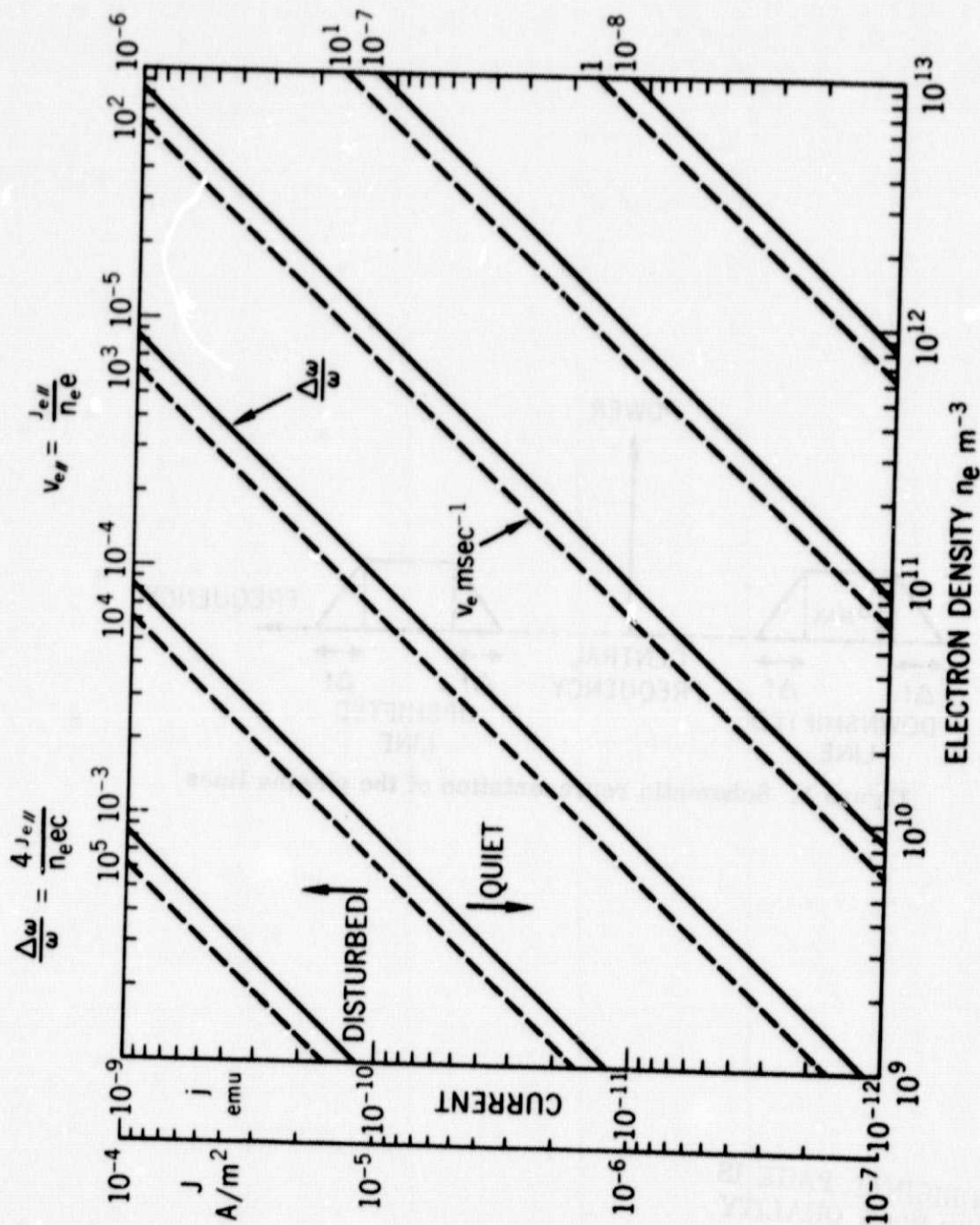


Figure 2. Diagram showing the inter-relationships of $\Delta\omega/\omega$, n_e , j , v_e